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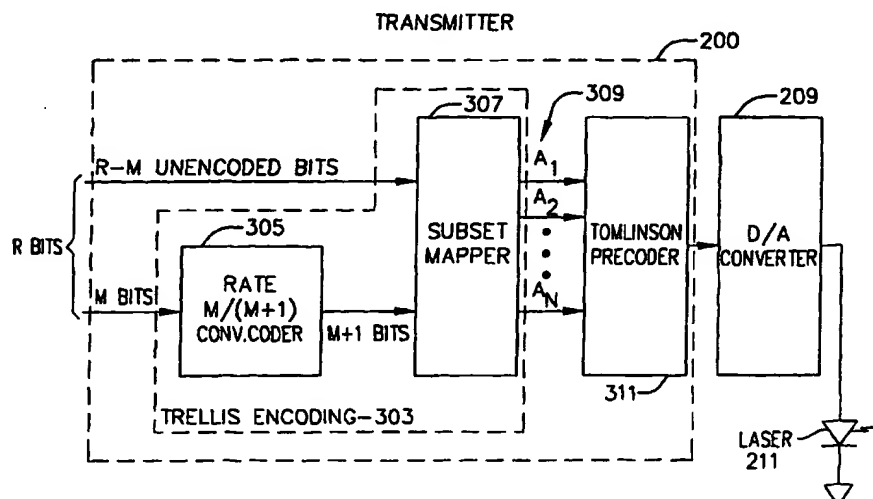
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(54) Title: **HIGH-SPEED TRANSMISSION SYSTEM FOR OPTICAL CHANNELS**



(57) Abstract: A method and apparatus for transmission of data on bandwidth limited fiber optic channels. A multilevel signaling alphabet having multiple levels of optical intensity are used to transmit signals on optical channels. In order to counteract the decrease in signal to noise ratio resulting from the use of a multilevel signaling alphabet over a bilevel signaling alphabet trellis encoding of the data to be transmitted is employed. To counteract intersymbol interference due to signaling faster than the Nyquist Rate, equalization methods such as Tomlinson-Harashima precoding and decision feedback equalization are employed.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

1 **HIGH-SPEED TRANSMISSION SYSTEM FOR OPTICAL CHANNELS**

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This Application claims priority from Provisional Application 60/177,034 entitled HIGH
SPEED TRANSMISSION FOR OPTICAL CHANNELS filed on 1/17/00, which is
incorporated by reference herein as though set forth in full.

FIELD OF THE INVENTION

10 The present invention relates generally to apparatus and methods for high speed data
transmission over optical channels, and, in particular embodiments, to transmission of data using
pulse amplitude modulation, trellis coding, and equalization techniques.

BACKGROUND OF THE INVENTION

15 The demand for higher capacity data transmission systems continues to increase. To
satisfy the ever increasing demand for more data transmission capacity higher baud rate systems
such as optical channels have been used. At high baud rates some optical fibers may exhibit
phenomena such as multimode transmission characteristics and intersymbol interference, which
can limit the signaling rate available on that fiber. Therefore, there is a need within the art for
methods and apparatus that are capable of higher baud rates, and for those which can compensate
20 for the problems encountered with high speed data transmission.

SUMMARY OF THE INVENTION

25 In one aspect of the invention, an apparatus for transmitting data on a fiber optic channel
is disclosed. The apparatus comprises a trellis encoder that accepts data to be transmitted, applies
a convolutional coding to a portion of the data, and produces a trellis coding of the data to be
transmitted. A subset mapper accepts the trellis coding and produces a plurality of pulse
amplitude modulated (PAM) symbols from the trellis coding. A Tomlinson precoder accepts the
PAM symbols and applies a Tomlinson precoding the PAM symbols. A converter converts the
PAM symbols into a form for coupling into a fiber channel.

30

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present invention will become
better understood with regard to the following description, appended claims, and accompanying
drawings where:

35 Figure 1 is a block diagram illustrating components of an optical data communication
system.

Figure 2 is a block diagram of a optical communication system according to an
embodiment of the invention.

1 Figure 3 is a block diagram illustrating a fiber optic transmitter according to an embodiment of the invention.

 Figure 4 is a graphical illustration of Tomlinson-Harashima precoding (THP).

5 Figure 4a is a graphical illustration of the mapping of excess pulse amplitude modulation levels which are produced by a Tomlinson-Harashima precoder.

 Figure 5 is a block diagram of a receiver, according to an embodiment of the invention.

 Figure 6 is a simplified block diagram of a receiver, which contains a decision feedback equalizer (DFE).

10 Figure 7 is a graphical illustration of the impulse response of an exemplary fiber channel.

 Figure 8 is a block diagram illustrating a fiber channel model used in conjunction with a laser model based on the rate equations.

 Figure 9 is a graph representing of the impulse response of a linear system having a Gaussian impulse response.

15 Figure 10 is a graph illustrating an output of a laser model based on the rate equations.

 Figure 11 is a graph illustrating an expanded portion of the graph illustrated in Figure 11.

 Figure 12 is a graph of the simulated output of the laser model of Figure 10 after passage through a simulated channel.

20 Figure 13 is an eye diagram of a simulated receiver equalizer, illustrating a transition between a bilevel training mode and receiving PAM-5 symbols.

 Figure 14 is a graph of a magnified portion of the graph of Figure 13, illustrating the convergence of the equalizer during a training sequence.

25 DETAILED DESCRIPTION OF THE INVENTION

 The demand for higher data carrying capacity transmissions systems continues to increase. Accordingly, embodiments of the present invention relate to methods and apparatus for increasing the rate of data transmission in optical transmission systems.

 Figure 1 is a block diagram illustrating a prior art optical data communication system.

30 In Figure 1 a data source 101 provides data to be transmitted over fiberoptic channel 109. Data source 101 may be, for example, the Internet, a cable television head end, a corporate network or a variety of other data sources.

 Data from data source 101 is provided to an encoder 103, which encodes the data. Encoding may encompass representing the input data from the data source 101 in a variety of ways. In the exemplary system of Figure 1 the data encoding comprises translating the data received onto a series of OOK (On Off Keying) symbols for transmission using a laser. OOK represents the data as a series of on-off pulses or two levels of optical intensity.

 Once the data is encoded, the encoded signal is coupled into an optical channel driver,

1 such as a laser driver 105, which controls the intensity of a laser 107. The output of laser 107 is coupled into a fiber optic channel 109. The fiber optic channel is further coupled to an optical receiver 111. The optical channel 109 may be of various lengths depending upon the application.

5 The optical receiver 111 accepts the signal provided by the fiber optic channel 109 and converts it into an electrical signal. The electrical signal, representing the transmitted data, is provided to an OOK data decoder 113. The data decoder 113 reverses the process of the encoder 103 and recreates the data provided by the data source 101. The data from the decoder may be then routed, for example using a data router 115, to various user devices. An exemplary user
10 device 117 then receives data, such as video data, from the data router 115.

Figure 2 is a block diagram of an optical communication system according to an embodiment of the invention. Transmitter 200 communicates with receiver 222 over channel 213. In Figure 2 the data to be encoded is coupled into a trellis encoder 201. The trellis encoder 201 includes convolutional coder 206 and subset mapper 203. The trellis encoder 201 may be
15 a single trellis encoder or it may be a series of trellis encoders in parallel.

The outputs of the convolutional coders 206 are further coupled into subset mappers 203. A subset mapper accepts the convolutionally encoded signal and produces multilevel symbols 205 as an output. The multilevel symbols are then coupled into equalizers 207. The equalizers 207 are used to compensate for the non-flat response of a channel 203. After equalizing the
20 multilevel symbols, the equalizers provide the resultant symbols to one or more digital to analog converters (D/A) 209. The digital to analog converters 209 accept the equalized multilevel symbols, and convert them into analog signals. The analog signals are then coupled serially into an optical source such as a laser 211. The digital to analog (D/A) converter(s) provide successive signals to laser 211 during a second time period, and so forth. In other words a signal from a first
25 D/A converter may be provided to the laser 211 during a first time period, then a signal from a second D/A converter may next be provided to the laser 211. In such a manner multiple symbols from multiple data sources may be transmitted by the single laser 211. Alternatively, a single D/A converter may accept successive values from multiple data sources, converting them into a series of analog values to be used to modulate the intensity of the laser output 211.

30 The output of the laser 211, modulated by the analog representation of the multilevel symbols, is coupled into the optical channel 213. The optical channel 213 transmits the intensity modulated laser signal to an optical-to-electrical converter 215. The optical-to-electrical converter 215 accepts the optical signal from the channel 213 and converts it back to an intensity modulated series of electrical signals. The optical-to-electrical converter 215 then provides the
35 amplitude-modulated signals to one or more analog-to-digital (A/D) converters 217. The A/D converters convert the series of analog signals to digital signals. The digital signals are provided to one or more trellis decoders 219 where the trellis-encoded digital signals are decoded. The output of the trellis encoders are provided to a physical coding sublayer (PCS) unit 221. A

1 physical coding sublayer (PCS) may provide bit manipulation, such as decoding, to the signals decoded by the trellis decoder 219. The data output of the PCS 221 is then provided to a user interface such as an XGMII (extended Gigabit Media Independent Interface).

5 Illustratively, the optical communication system depicted in Figure 2 has particular characteristics. For example, the channel 215 is considered to be a standard 62.5/125 μm fiber. Fiber is commonly specified in terms of a bandwidth times length product. For a 62.5/125 μm meter fiber a typical bandwidth times length product is 500 MHz/km. 500 meters of such fiber would typically yield a 1 gigahertz bandwidth for a laser wavelength of 1310 nanometers.

10 To transmit a signal at or less than the Nyquist rate, the minimum bandwidth must equal one half of the symbol rate of the channel. The Nyquist bandwidth of a channel is the maximum rate at which signaling can occur on that channel without intersymbol interference (ISI). In other words, a system cannot transmit signals faster than the Nyquist rate without intersymbol interference. However, an equalizer such as 207 can be used to remove intersymbol interference. Equalization in Figure 2 is shown within the transmitter 200. Such equalization is called transmit
15 side equalization. Equivalently, equalization may be applied at the receiver 223, and either equalization may be non-linear. For example, decision feedback equalization (DFE) may be used at the receiver 223. Although the equalization can be done equivalently on the transmitter as well as the receiver side, there are certain advantages to placing the equalizer in the transmit side. For example, if the equalization is placed within the receiving side, the trellis decoder and an
20 equalizer must function concurrently. Concurrent trellis decoding and equalization is a complication within the receiver that can be avoided by having the equalization circuit in the transmitter. It is difficult to combine an equalizer and a trellis decoder, in a receiver, because such a receiver would have to decode the trellis while attempting to compensate for the intersymbol interference. If the equalization is done in the transmitter, there is no necessity to
25 compensate for intersymbol interference while decoding the trellis coding.

Embodiments of the present invention may include, for example, a single trellis encoder, a single symbol mapper, a single equalizer etc. Alternatively, the same components may be replicated multiple times the signals time multiplexed from such parallel components in order to couple them in and out of a single fiber channel. To simplify the disclosure, however, the
30 components will be illustrated as single components. Those skilled in the art will realize that the same components may be used in a variety of parallel configurations.

For the purposes of example, the multilevel symbols 205 are considered to be part of a PAM-5 (pulse amplitude modulation - 5 level) alphabet.

Figure 3 is a block diagram illustrating the fiber optic transmitter 200 according to an
35 embodiment of the current invention. Detail of the transmitter 200 is illustrated in Figure 3. The trellis encoder 323 accepts a group of R bits from the data source 202. The trellis encoder 305 is a rate $M/(M+1)$ convolutional coder of the R bits which are input to the rate $m/(M+1)$ encoder. R-M bits will be unencoded and M bits will be encoded. The output of the convolutional coder

1 305 comprises $(M+1)$ bits. The R-M unencoded bits and the $M + 1$ coded bits, which are output
from the convolutional coder 305 are provided to a subset mapper 307. The subset mapper 307
maps the received bits into a series of multilevel symbols 309, for example, PAM 5. The
combination of convolutional coder 305 and the R-M unencoded bits comprises a trellis encoder
5 323. The pulse amplitude modulated signals A_1 through A_N have 5 levels, but may have any
number of amplitude levels, depending on the pulse amplitude modulation scheme chosen.

The fiber optic channel, as discussed above, illustratively exhibits multimode transmission
characteristics at any Nyquist bandwidth of 1 GHZ. Accordingly, the bandwidth available in the
channel is smaller than required to signal without intersymbol interference (ISI) at a 10 GHZ rate.
10 To achieve the 10 GHZ signaling rate, the channel operates in the presence of intersymbol
interference. One way to compensate for intersymbol interference is to use an equalizer in the
receiver. For example, a decision feedback equalizer (DFE) may be used. The DFE is discussed
in the receiver section.

A further way to compensate for the effect of intersymbol interference is to use a
15 Tomlinson precoder 311.

In Figure 3 multilevel symbols 309 are provided to a Tomlinson Precoder. for example
in a 10 gigabit per second (GPS) transmission system implemented using a five level pulse
amplitude modulation - 5 level (PAM-5) transmission scheme. The baud rate necessary to
achieve a 10 GPS transmission is reduced to five gigabaud because each PAM-5 symbol can
20 represent five different values.

There are multiple advantages to reducing the baud rate by using pulse amplitude
modulation. One advantage is that the system can operate over multimode and limited bandwidth
channels over greater distances than would be possible if on/off keying (OOK) were used.
Another advantage, of using PAM instead of OOK, is that the PAM symbols can represent
25 multiple bits of information. Accordingly, the speed of the electronic circuits needed to create
the transmitted signal at the transmitter is reduced. Consequently, the speed of the electric
circuits needed at the receiver is also reduced. By reducing the required speed of the electronic
circuits, technology such as CMOS (complimentary metal oxide semiconductor) may be used to
implement the electronic circuitry. In contrast, high speed electronic circuits can often require
30 expensive high speed technology such as gallium arsenide or indium phosphide. Because of the
higher levels of integration presently available using CMOS, a greater level of integration is
possible than with such technologies as gallium arsenide or indium phosphide, and so it is
advantageous to use PAM symbols to decrease the signaling rate while keeping the baud rate
constant.

35 A potential disadvantage of using multilevel encoding such as PAM-5, instead of the more
traditional on/off keying, is that a higher signal to noise ratio (SNR) may be required of the
channel since OOK needs to represent only two levels whereas PAM symbols are multiple levels.
By using multiple levels the distance between levels is reduced, over using two levels. Because

1 the distance between levels is reduced the available noise margin is also reduced. To reduce the required signal to noise ratio to a level equivalent to the OOK system, PAM-5 modulation may be combined with trellis coding as illustrated in the embodiment of the invention illustrated in Figure 3.

5 In Figure 3 a Tomlinson Harashima (Tomlinson) precoder 311 functions as a transmit side equalizer. A traditional equalizer in a receiver compensates for distortion and uneven frequency response caused by the transmission channel. Including the fiber on laser equalization, however, can be done equivalently in a receiver or a transmitter. In either case the result is a signal characteristic that, when combined with the channel characteristic, ideally results in a flat overall response.

10 A problem with attempting to equalize a fiber channel is that the fiber may exhibit nulls. In other words, the fiber channel transfer function permits very little signal transmission at a particular frequency. An equalizer, attempting to compensate for such nulls, may require an high gain to make up for the poor response of the channel. High gain may produce an unstable response in the equalizer.

15 Tomlinson Harashima precoding may be used to compensate for frequency nulls within the channel. The output of the Tomlinson precoder 311 is provided to a Digital Analog (D/A) converter 313. The D/A converter produces an analog signal, which is used to modulate the intensity of the laser 211. The Tomlinson precoder is shown as a simplified representation in 311. The Tomlinson precoder 311 may actually be a group of Tomlinson precoders, each of which operates on one PAM-5 symbol. The PAM-5 symbols thus generated are multiplexed into the D/A converter 313.

20 Figure 4 is a graphical illustration of Tomlinson-Harashima precoding (THP). In Figure 4, Channel 411A, which is identical to Channel 411B, can be described by a Z transform. The characteristics of Channel 411A and 411B can be described by the expression " $1+D(Z)$." The term " $D(Z)$ " term is responsible for the intersymbol interference exhibited by the channel. If it is desired to compensate for the characteristic of the channel within the transmitter, a filter with a transfer characteristic inverse of the channel must be added. By implementing a feedback loop comprising the summation unit 405A and the feedback filter 407A, a transfer characteristic of $1/(1+D(Z))$ is created. The total response would then be $1/(1+D(Z))$ times $1+D(Z)$ resulting in a net channel characteristic of one, which is the combined response of the precoder and the channel. The combined response of the precoder and the channel is therefore a flat response which does not introduce any dispersion, and therefore, the signal at the receiver 413A is equalized.

35 Difficulties can be encountered because at frequencies where the channel has a lot of attenuation, the precoder will have a lot of gain to compensate for the attenuation. At such frequencies, the precoder may become unstable. Therefore, in order to stabilize the precoder and to limit the amplitude of the signal out of the precoder, a signal V_n represented by arrow 403 is

1 added to the summation unit 405A. $V_n = K_n \times M$ where M is the number of levels being
transmitted on the channel. In the present embodiment, which uses PAM-5, M has a value of 5.
5 M is essentially the maximum number of levels desired at the output. Once the output signal of
the precoder, V_n is computed, if the signal exceeds certain limits then V_n is subtracted from the
signal Y_n and K_n is the smallest integer that brings the output Y_n back into the desired range.
There is always a value for K_n that will meet this condition. M is essentially the maximum
allowable range of the output of the precoder. Depending on the value of Y_n there is a unique
integer value K_n that will bring the output of the precoder back within the range M . This is the
10 basis of Tomlinson Harashima Precoding (THP). In other words, the THP does the inverse
channel characteristic filtering then modifies the input to the summation unit by adding an
integral multiple of M which at the output is bounded. The signal V_n is added to the input. The
output of the channel sees a quantity equal to X_n plus V_n . In other words, the number of levels
appearing at the receiver has been expanded. Therefore, the slicer in the receiver must be able
to distinguish $X_n + V_n$ levels instead of just being able to distinguish X_n levels. One price for
15 doing this type of equalization is the increase of the number of levels in the constellation at the
receiver. Therefore, all that needs to be done in the receiver to recover the original PAM-5 levels
is to implement a wrap-around scheme such that the excess levels are wrapped around into the
original PAM-5 levels. The wrap around is illustrated in Figure 4A.

Figure 4A is a graphical illustration of the mapping of excess pulse amplitude modulation
20 levels produced by a THP, such as illustrated in Figure 4. In Figure 4A, 9 PAM constellation
levels are present. The correct PAM-5 levels, that is 435, 437, 439, 441 and 443 are present. In
addition, levels 431 and 433 which are higher than the highest PAM level 445, are present.
Additionally, levels 445 and 447 are present which are lower than the lowest level 443 are
present. In order to map the 9 levels back into the original 5 levels, a modulo type add or subtract
25 is done. In other words, if the level out to be remapped are above the maximum levels, a modulo
5 value is subtracted. In the present case, 5 levels are subtracted from level 433, and accordingly
level 433 maps into level 443. Similarly, 5 levels are subtracted from level 431 and level 431
maps into level 441. Similarly level 445, which is below the lowest level of 443, has 5 levels
added to it and level 445 is thereby mapped into level 435. Similarly, level 447, which is below
30 the lowest level of 443, has 5 levels added to it and is thereby remapped into level 437. If for
example 6 levels were present above level 435 then 10 would be subtracted from the 6th level and
the 6th level above 435 would map into level 443.

Referring to Figure 4 precoder 400B illustrates an alternate method of adding the
correction factor V_n to the precoder. In precoder 400A signal Y_n is examined and then a value
35 for K_n is decided on and the value V_n is then added or subtracted in the summation unit 405A.
In reality the operation of creating the adjustment value V_n is nothing more than a wrap around
operation. The operation is comparable to the overflow in an accumulator. Therefore, in the
precoder represented in 400B modulo block 417 is added. In the modulo M block 417, a wrap

1 around operation is added to the precoder circuit and automatically accomplishes the adjustment
accomplished by the summation for the V_n signal in summation block 405A in precoder 400A.

5 One problem with Tomlinson precoding is that the number of levels in the receiver may
grow depending on the channel characteristics. For example, in a PAM-5 system the number of
levels may grow to 15, 20 or more. The proliferation of levels in the receiver may be a problem
because within the receiver is an A/D converter sampling the multiple received levels. In order
to accommodate multiple levels, the resolution of the A/D converter can be adversely impacted
10 because the levels must be scaled so that they fit within the range of the A/D. That is, the
resolution of an A/D converter discriminating between 5 levels is much better than the resolution
of that same A/D converter discriminating 15 levels. Therefore, adding levels can require a better
A/D converter, that is one having more bits of resolution. It is therefore desirable to limit the
number of levels presented to the receiver. The number of levels that are presented to the
15 receiver can be accomplished by limiting the value of K_n in precoder 400A. Such limiting may
lead to certain points falling outside of the allowed levels, however in return for the points falling
outside of the allowed levels, the number of levels presented to the receiver can be limited. This
form of THP is referred to as Dynamics Limited Precoding (DLP).

Precoding has several advantages over receiver side equalization. One advantage is that
a precoder lends itself to a better parallel implementation than receiver side equalization such as
20 Decision Feedback Equalization (DFE). Another advantage of receiver side equalization is that
when using trellis-coded modulation, precoding allows the trellis decoder to be substantially
simplified, since the decoder then does not have to deal with intersymbol interference. The
combination of precoding with trellis coded modulation can approach the Shannon bound for
channel capacity when good modulation codes are used. Therefore, the present architecture can
25 provide a close to optimal architecture.

Figure 5 is a block diagram of a receiver, according to an embodiment of the invention,
illustrating the decoding of multiple signals transmitted across the same channel. In Figure 5,
a photo detector 501 accepts a pulse amplitude modulated signal from the fiber optic channel
109. The photo detector 501 then provides a voltage signal, representative of the signal received
30 from the fiber optic channel 109, to a pre-amplifier 503. The pre-amplifier 503 amplifies the
signal provided by the photo detector 501 to a suitable level. Pre-amplifier 503 then provides the
amplified signal to a high pass filter 505.

High pass filter 505 functions to prevent a phenomenon known as baseline wander. High
pass filtering the input signal blocks low frequencies thus minimizing low frequency excursions.
35 Photo detector 501, pre-amplifier 503 and high pass filter 505 generally define the optical
receiver 111. The boundaries, however, between the optical receiver and decoder are somewhat
arbitrary and other sources may define boundary line between these blocks differently.

The output of high pass filter 505 is provided to a programmable gain amplifier (PGA)

1 507. The gain of the PGA 507 is controlled by an automatic gain control (AGC) circuit 508.
AGC circuit 508 controls the gain of the amplifier 507 according to signal levels at the output
of the retiming block 511. The signal at the output of the PGA 507 comprises a series of high
speed pulse amplitude modulated voltage signals. The output of the programmable gain
5 amplifier 507 is coupled into a plurality of interleaved analog to digital converters 509.

The analog to digital converters (A/D) 509 are timed by a clock provided by the timing
recovery circuit 515. Each A/D converter, however, receives its own phase of the clock in order
to sample successive values using successive A/D converters. Because the values received by
the A/D converters are sampled using a clock having different phases, retiming of the signals is
10 necessary in order to create a synchronized parallel value. The retiming of the A/D samples takes
place in retiming block 511. Retiming block 511 essentially comprises a clocked register circuit
or equivalent. By interleaving N A/D converters in the analog to digital block 509, the clock rate
of each individual converter can be reduced by a factor of N (over the use of a single converter).
Without the interleaving of analog to digital converters 509 it may be difficult or impossible to
15 fabricate an analog to digital converter, which could sample the input at a high enough rate, in
order not to lose any successive values in the input data stream. By interleaving the A/D
converters the necessity of using very high speed circuit technologies, such as gallium arsenide
or indium phosphide may be avoided.

Parallel values from the retiming block 511 are provided to a fine AGC module 513. The
20 digital values of the synchronized parallel data can be examined in the fine AGC modules to
determine whether the amplitude of the input signal is correct and to provide fine adjustments
to the signal values. The timing recovery block 515 may adjust the timing of the analog to digital
converters.

The output of the fine AGC block 513 is coupled into an N-dimensional trellis decoder
25 519. An N-dimensional trellis decoder includes N trellis decoders. The number of trellis
decoders will vary depending on a variety of implementation details. The N-dimensional trellis
decoder 519 decodes the symbols accepted from the fine AGC module 513 and converts them
into digital data values.

Once the PAM-5 symbols have been decoded into bit patterns, they are provided to a
30 physical coding sublayer (PCS) 521. The physical coding sublayer 521 provides bit
manipulation, such as signal descrambling, etc. The physical coding sublayer 521 then provides
a resultant bit stream to a system interface 523.

Figure 6 is a simplified block diagram of a receiver such as that illustrated in Figure 5
illustrating the addition of a DFE. The DFE in the receiver may be used instead of a Tomlinson
35 precoder in the transmitter. Because equalization can be done equivalently in the receiver or
transmitter the net equalization effect is the same.

The block diagram of Figure 6 does not illustrate the parallelism of the receiver illustrated
by Figure 5. Figure 6, however does provide detail on the addition of equalization, which may

1 be included in the receiver. A photonic signal is accepted by the detector 601. The detector 601
converts the received signal into a voltage and then provides the voltage signal to pre-amplifier
603. Pre-amplifier 603 amplifies the signal and provides it to high pass filter 605. A
programmable gain amplifier 607 accepts the signal from the high pass filter 605 and provides
5 it to an A/D converter 609.

The A/D converter 609 converts the analog signal from the high pass filter into a digital
equivalent. An AGC block 608 accepts the digital value from the A/D converter 609 and
controls the gain of the programmable gain amplifier (PGA) 607. The output of the analog to
digital converter 609 is also provided to a fine AGC 613, where small adjustments in the signal
10 are made. The output of the fine AGC 613 is then provided to a decision feedback equalizer 625.
In order to explain the operation of a decision feedback equalizer reference will be made to
Figure 7.

Figure 7 is a graphical illustration of the impulse response of an exemplary fiber channel.
In Figure 7, point 719 represents a decision point where the value of the waveform 729 is
15 sampled. Since the input waveform is an impulse, by definition only one value (represented by
point 719) is provided to the channel. Therefore any subsequent response such as values 721,
723, 725 or 727 do not represent valid values which have been provided to the channel. Values
721, 723, 725 and 727 instead represent intersymbol interference caused by the impulse function.
Samples 721, 723, 725 and 727 may be caused by the dispersion of the impulse waveform within
20 a multimode fiber and are an undesirable feature of the fiber channel. They are generally caused
by the differing propagation times of the impulse through different modes of the fiber. An
equalizer, such as the illustrated DFE 625 may compensate for the distortion introduced by
samples such as 721, 723, 725 and 727. The decision feedback equalizer uses an adaptive
transversal filter 711 to generate a waveform equivalent to the trailing edge 731 of the impulse
25 response. The trailing edge, represented by 731, is the portion of the waveform immediately after
the sampled point 719 which includes spurious response points 721, 723, 725 and 727. The
portion of the waveform 719 represents the spurious response of the channel. The adaptive
transversal filter 623 makes a copy of the spurious response and subtracts it from the overall
channel response in summation unit 619. The adaptive transversal filter is termed adaptive
30 because it must adapt itself to the characteristics of the channel. In other words, the adaptive
transversal filter must be trained using the channel characteristics in order to derive the proper
response that will be provided to the summation unit 619. Once the slicer 621 detects which
symbol is present, the adaptive transversal filter can then provide the response necessary to cancel
the intersymbol interference present that would accompany the transmitted point.

35 The received waveform at a point prior to the summation unit 619 is shown on
oscilloscope 615 as display 615A. Display 615A is a scatter type waveform that does not exhibit
distinct levels. The waveform 631 may be generated by the adaptive transversal filter 611, in
order to cancel the intersymbol interference (ISI) within the channel.

1 Once the intersymbol interference is subtracted from the incoming signal in summation
unit 619, the output of the summation unit appears as shown on oscilloscope 617, in display
617A. Display 617A represents an eye diagram having five discrete levels. Once the levels have
5 been well defined, as seen on display 617A, the slicer 621 is able to distinguish relatively easily
between the symbols. The adaptive transversal filter 623 will respond to whatever symbol is
found by the slicer 623 and provide the necessary waveform to cancel the intersymbol
interference caused by the found symbol's transmission. The transversal filter generating an
intersymbol interference replica, which must be subtracted from the incoming signal. The
10 intersymbol interference waveform changes, depending on which symbol has been found by the
slicer. The output of the decision feedback equalizer depends on the previously decoded
symbols. The PAM-5 symbols found are then decoded by the Physical Coding Sublayer (PCS)
521 and then provided to an interface such as a XGMII interface (not shown).

To further set forth the inventive concepts, a preliminary simulation study of a PAM-5
system is discussed. To simulate the PAM-5 system a laser model was created using rate
15 equations. Pseudo-random PAM-5 data was introduced to the laser model. The output from the
laser model was provided to fiber model. The fiber modeled was a multimode type fiber modeled
as a linear system with Gaussian Impulse Response. In one example a 62.5/125 μm fiber having
a bandwidth of 1 GHZ conveys a loss nanometer signal.

The Nyquist theorem establishes that the bandwidth needed to transmit data at a rate F_b ,
20 $= 1/T$, without intersymbol interference, must be larger than or equal to $\frac{1}{2} T$. Many
communication systems however, signal at rates faster than $0.5 F_b$, using special techniques to
control the intersymbol interference. Such techniques have been used in the 100Base-TX and
1000Base-T Ethernet transceivers. The present model examines signaling at 5 GBaud over
multimode fibers with 1 GHZ bandwidth. The present simulations contemplate signaling at 2.5
25 times the Nyquist rate (data rate equals 10 Gb/s, baud rate $F_b = 5 \text{ GHZ}$, bandwidth equals 1
GHZ). This bandwidth assumption is consistent with 500 meters of 160/500 MHz-KM fiber at
1350 nanometers (nm), or 160 meters of the same fiber at 850 nm.

The model also assumes a receiver having a DFE as illustrated in Figure 6. It is
30 recognized that equivalent equalization can be accomplished at the transmitter through the use
of THP, DLP or other equalization techniques.

The rate equations used in modeling the laser are described in "On Approximate
Analytical Solutions of the Rate Equations for Studying Transient Spectra of Injection Lasers",
by D. Marcuse and T.P. Lee, IEEE Journal of Quantum Electronics, September 1983. The
equations of the computer model are solved numerically using a fourth order Runge-Kutta
35 Algorithm. The bias current in the equations was set to three times $I_{\text{threshold}}$. In addition, a 6dB
extinction ratio is used.

Figure 8 is a block diagram illustrating a channel model used in conjunction with the rate
equations. In Figure 8, a pseudo-random PAM-5 symbol generator 801 provides symbols to the

1 laser model 803. The output of the laser model is then provided to a multimode fiber model 805.
The fiber model 805 is a linear system having a Gaussian impulse response.

5 Figure 9 is a graphic representing the impulse response of a linear system having a Gaussian impulse response convolved with a single pole high pass filter with corner frequency of 200 MHz. For the simulation, the fiber channel is modeled as in an article "Equalization of Multimode Optical Fiber Systems," by B.L. Kaspers, Bell Systems Technical Journal, September 1982. The Kaspers' model comprises a linear dispersive system with a Gaussian impulse response given by equation 1. Such Gaussian impulse response models are common throughout the literature and are considered to be fairly accurate for fibers in which all modes are excited
10 equally (i.e. multimode fibers in an overfill launch condition).

$$h(t) = \frac{1}{\sqrt{2\pi} \cdot \alpha T} \cdot e^{-[t^2 / (2(\alpha T)^2)]}$$

15 (Equation 1)

Where T is the period and α is a system dependent variable related to the bandwidth of the fiber. The corresponding frequency response of the channel is given by equation 2.

$$H(f) = e^{-[(2\pi\alpha T)^2 / 2]}$$

20 (Equation 2)

The 3 dB bandwidth of the fiber is given by a equation 8 for a given baud period equal to 300 pico seconds.

25
$$f_{3dB} = \frac{0.1325}{\alpha T}$$

(Equation 3)

30 If the 3 dB bandwidth of the system is assumed to be one gigahertz, the value of α is equal to 0.6625.

Figure 10 is a graph illustrating the output of a laser model based on the rate equations. The vertical axis 1001 represents the intensity of the laser.

35 As can be seen from Figure 10, the signal appears to be somewhat noisy. The noise is partially accounted for by relaxation oscillation of the laser. Each time there is a sharp transition in the laser signal, overshoot and ringing results, as depicted in the graph of Figure 10.

Figure 11 is a magnified portion of the graph of Figure 10. Figure 11 is included to illustrate the ringing present within the waveform of Figure 10.

Figure 12 is a graph of the waveform of Figure 10 after passage through the fiber channel

1 model. In other words, Figure 12 is an illustration of the waveform presented to the receiver. As can be readily appreciated by observing Figures 10 and 12, the fiber channel performs significant filtering on the output of the laser. In other words, Figure 12 is a convolution of the waveform in Figure 10 with the impulse response of the channel as illustrated in Figure 9.

5 Figure 13 is an eye diagram of a simulated equalizer at the transition between a training mode and receiving PAM-5 symbols.

The simulated signal of Figure 12 is introduced to a receiver in Figure 13. The receiver used is one such as illustrated in Figure 6. The eye diagram depicted in Figure 13 is the output of the decision feedback equalizer 625 of Figure 6. The portion of the graph in Figure 13 delineated by 1301 represents a scatter diagram equivalent to the display 615(a) of Figure 6. The scatter diagram results after data has begun entering the receiver and being processed by the slicer but the equalizer has not yet been trained. In other words, the adaptive transversal filter has not yet adapted to the characteristics of the channel. A portion of the graph illustrated at 1303 in Figure 13 is an illustration of the equalizer being trained using two level symbols. At point 1315, within Figure 13, the five level Pam alphabet is transmitted to the receiver. The results of the receiving of the five level Pam -5 alphabet in the trained decision feedback equalizer 625 is the five levels 1305, 1307, 1309, 1311, and 1313 depicted in Figure 13. Figure 14 is a graph of a magnified portion of the graph of Figure 13, illustrating the convergence of the equalizer during a training sequence.

20 Figure 14 is a time expansion of the section 1301 of Figure 13. As can be seen from Figures 13 and 14, high data rates can be achieved using pulse amplitude modulation despite the presence of inner symbol interference, which may result from signaling faster than the Nyquist rate.

25 As can be seen from the models used to simulate the PAM-5 system transmitting data a faster than the Nyquist rate is viable using the techniques disclosed. Additionally using multilevel symbols has been shown to be viable and may be used to increase the data rate across fiber channels. The reduced noise tolerance of the system due to the reduced distance between signaling levels of a multilevel signaling system may be counteracted by the use of trellis coding the signals transmitted.

30 Supplemental material with regard to the invention here and above described in Appendix A entitled "10Gb/s PMD Using PAM-5 Trellis Coded Modulation".

35

1 WHAT IS CLAIMED IS:

1. A method for high-speed transmission of information data on an optical channel,
the method comprising:
5 encoding information via a trellis encoder to produce digital multilevel symbols;
converting the digital multilevel symbols into analog multilevel signals; and
transmitting the analog multilevel symbols over an optical channel.
2. The method of claim 1 further comprising equalizing the digital multilevel symbols
10 to compensate for characteristics of the optical channel.
3. The method of claim 1 further comprising of equalizing the analog multilevel
symbols to compensate for characteristics of the optical channel.
- 15 4. The method of claim 2 wherein equalizing the digital multilevel symbols comprises
precoding the digital multilevel symbols using a Tomlinson Harashima precoder.
5. The method of claim 2 wherein the equalizing the digital multilevel symbols
comprises precoding the digital multilevel symbols using a dynamic limiting precoder.
20
6. The method of claim 1 wherein the converting the digital multilevel symbols to
analog multilevel symbols includes mapping the digital multilevel symbols into a subset mapper.
7. The method of claim 1 wherein transmitting the analog multilevel symbols over an
25 optical channel comprises modulating the intensity of a light source according to the level of the
analog multilevel symbols.
8. The method of claim 1 wherein transmitting the analog multilevel symbols over an
optical channel comprises modulating laser intensity according to a level of the analog multilevel
30 symbols.
9. A method as in claim 2 wherein equalizing the digital multilevel symbols to
compensate for the laser and channel characteristics comprises:
characterizing the channel; and
35 applying an inverse characterization of the channel to the digital multilevel
symbols:
10. A method as in claim 2 wherein equalizing the digital multilevel symbols to

1 compensate for the laser and channel characteristics comprises:
 characterizing the channel; and
 applying an inverse characterization of the channel to the analog multilevel
5 symbols.

11. A method for high speed transmission on an optical channel, the method
comprising:

 accepting information from a plurality of sources;
 encoding the information via a plurality of trellis encoders to produce a plurality
10 of digital multilevel symbols;
 converting the plurality of digital multilevel symbols into a plurality of analog
multilevel signals; and
 transmitting the analog multilevel signal by time division multiplexing the plurality
of analog multilevel signals onto an optical channel.

12. A method as in claim 11 wherein converting the plurality of digital multilevel
symbols to analog multilevel signals further comprises:

 mapping the digital multilevel symbols in a subset mapper; and
 forming analog multilevel symbols by providing analog representations of mapped
20 multilevel signals.

13. The method of claim 11 further comprising equalizing the plurality of digital
multilevel symbols to compensate for characteristics of the optical channel.

14. The method of claim 11 further comprising equalizing the plurality of analog
multilevel symbols to compensate for characteristics of the optical channel.

15. The method of claim 13 wherein equalizing the digital multilevel symbols
comprises precoding the plurality of digital multilevel symbols using a Tomlinson Harashima
30 precoder.

16. The method of claim 12 wherein equalizing the digital multilevel symbols
comprises precoding the plurality of digital multilevel symbols using a dynamic limiting
precoder.

17. The method of claim 11 wherein converting the plurality of digital multilevel
symbols into a plurality of analog multilevel symbols further comprises:
 accepting the plurality digital multilevel symbols into a subset mapper; and

1 forming a plurality of mapped analog multilevel symbols from the plurality of
digital multilevel symbols.

5 18. The method of claim 11 wherein transmitting the plurality of analog multilevel
symbols over an optical channel comprises modulating the intensity of a light source according
to the levels of the plurality of analog multilevel symbols.

10 19. The method of claim 11 wherein transmitting the plurality of analog multilevel
symbols over an optical channel comprises modulating the intensity of a laser according to the
level of the analog multilevel symbols.

20. The method as in claim 12 wherein equalizing the digital multilevel symbols to
compensate for the laser and channel characteristics comprises:
characterizing the channel; and
15 applying an inverse characterization of the channel to the digital multilevel
symbols.

20 21. The method as in claim 12 wherein equalizing the digital multilevel symbols to
compensate for the laser and channel characteristics comprises:
characterizing the channel; and
applying an inverse characterization of the channel to the plurality of analog
multilevel symbols.

25 22. The method as in claim 11 wherein converting the plurality of digital multilevel
symbols into a plurality of analog multilevel signals comprises:
accepting the plurality digital multilevel symbols successively into a single analog
to digital converter; and
successively converting the plurality of symbols into analog multilevel symbols.

30 23. The method as in claim 11 wherein converting the plurality of digital multilevel
symbols into a plurality of analog multilevel signals comprises:
accepting the digital multilevel symbols successively into a plurality of analog to
digital converters;
converting the plurality of symbols into an analog representation; and
35 successively combining the analog multilevel symbols into a succession of analog
multilevel symbols.

24. A method of receiving data from an optical channel the method comprising:

- 1 accepting a multilevel signal from the channel into an optical to electrical
converter;
 converting the multilevel signal into an analog electrical signal;
 converting the analog electrical signal into a digital signal; and
5 decoding the digital signal in a trellis decoder.

25. The method of claim 24 further comprising equalizing the digital signal prior to
decoding the digital signal in the trellis decoder.

- 10 26. The method of claim 25 wherein equalizing the digital signal comprises applying
a decision feedback equalization to the digital signal.

27. A method as in claim 24 wherein converting the analog electrical signal to a digital
signal comprises:
15 successively sampling the analog electrical signal; and
 converting the successive samplings into a plurality of parallel digital values.

28. A method of signaling over an optical channel the method comprising:
 accepting data from a source;
20 trellis encoding the data;
 coupling the encoded data into an optical channel;
 conveying the data over the optical channel;
 accepting data from the optical channel
 decoding the data accepted from the optical channel; and
25 providing the decoded data to an interface.

29. A method as in claim 28 further comprising:
 equalizing the data after trellis encoding the data.

- 30 30. A method as in claim 29 wherein equalizing the data comprises applying a
Tomlinson-Harashima precoding to the data.

31. A method as in claim 30 wherein equalizing the data comprises applying a dynamic
limited precoding.

- 35 32. An apparatus for transmitting information on an optical channel to apparatus
comprising:
 a trellis encoder for accepting digital information and producing digital multilevel
signals;

1 a digital to analog converter that accepts the digital multilevel signals and produces
analog multilevel signals; and
 an analog signal to optical converter that converts the analog signal to an optical
level for coupling into an optical channel.

5

33. The apparatus of claim 32 further comprising an equalizer that accepts the digital multilevel signals and produces equalized digital multilevel signals prior to coupling into the digital to analog.

10

34. The apparatus of claim 32 further comprising an equalizer that accepts the analog multilevel signals and produces equalized analog multilevel signals.

35. An apparatus as in claim 33 wherein the equalizer is a Tomlinson-Harashima precoder.

15

36. An apparatus as in claim 33 wherein the equalizer is a dynamic limiting precoder.

37. An apparatus as in claim 32 wherein the analog signal to optical level converter includes a laser.

20

38. An apparatus for concurrently transmitting a plurality of data signals over an optical channel, the apparatus comprising:

a plurality of trellis encoders that accept a plurality of data signals and produce a plurality of digital multilevel signals;

25

a converter that accepts a plurality of digital multilevel signals and produce a plurality of analog multilevel signals;

an optical source that receives the plurality of analog multilevel signals and produces a light output proportional to the level of successive analog multilevel signals for driving an optical channel.

30

39. An apparatus as in claim 38 further comprising a plurality of equalizers that accept the plurality of digital multilevel signals and produce a plurality of equalized digital multilevel signals to provide to the converter.

35

40. An apparatus as in claim 39 wherein the plurality of equalizers comprise a plurality of Tomlinson-Harashima precoders.

41. An apparatus as in claim 39 wherein the plurality of equalizers comprise a plurality

1 of dynamic limiting precoders.

42. An apparatus for concurrently transmitting a plurality of data signals over an optical channel the apparatus comprising:

5 a plurality of trellis encoders that accept a plurality of data signals and produce a plurality of digital multilevel signals;

an analog to digital converter that sequentially accepts the plurality of digital multilevel signals and produces a plurality of sequential analog multilevel signals;

10 an optical source that receives the plurality of analog multilevel signals for driving an optical channel.

43. An apparatus as in claim 38 further comprising a plurality of equalizers that accept the plurality of digital multilevel signals and produce a plurality of digital multilevel signals.

15 44. An apparatus as in claim 43 wherein the plurality of equalizers comprise a plurality of Tomlinson-Harashima precoders.

45. An apparatus as in claim 43 wherein the plurality of equalizers comprise a plurality of dynamic limiting precoders.

20

46. An apparatus for receiving data from an optical channel the apparatus comprising:
an optical to electrical converter for receiving an optical multilevel signal from an optical channel and converting the optical multilevel signal into an analog multilevel electrical signal;

25 a decoder that accepts the analog multilevel electrical signal and converts it into digital multilevel signal;

a trellis decoder that accepts and decodes the digital multilevel signal producing data.

30 47. The apparatus of claim 46 further comprising an equalizer for accepting the digital multilevel signal and producing a digital equalized multilevel signal for coupling into the trellis decoder.

48. An apparatus as in 47 wherein the equalizer is a decision feedback equalizer.

35

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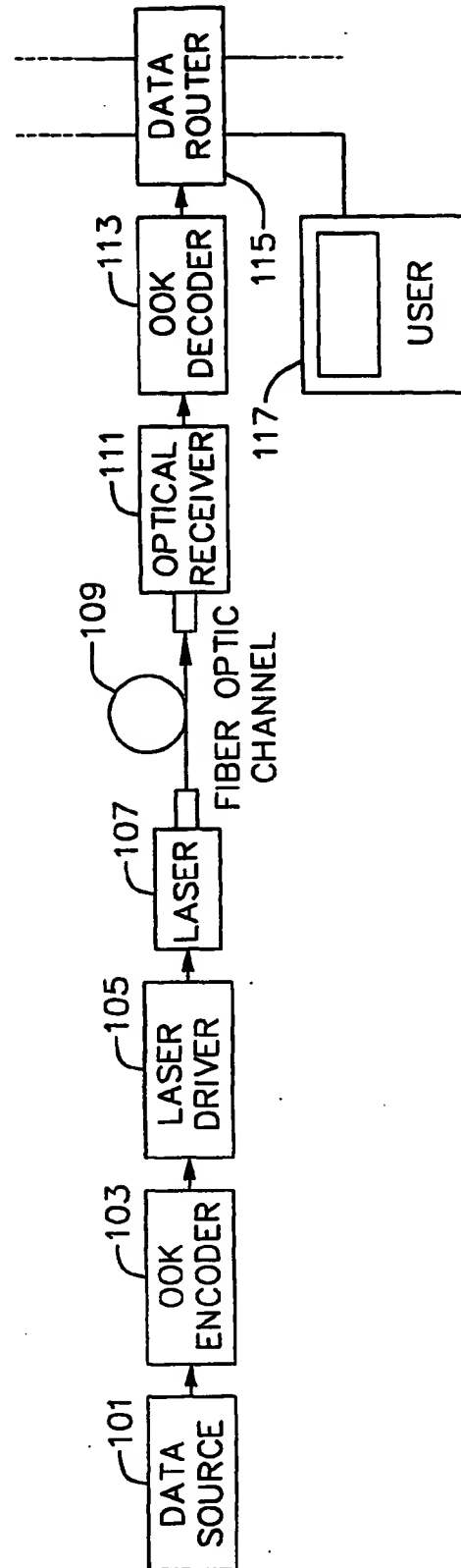
FIG. 1PRIOR ART

FIG. 2

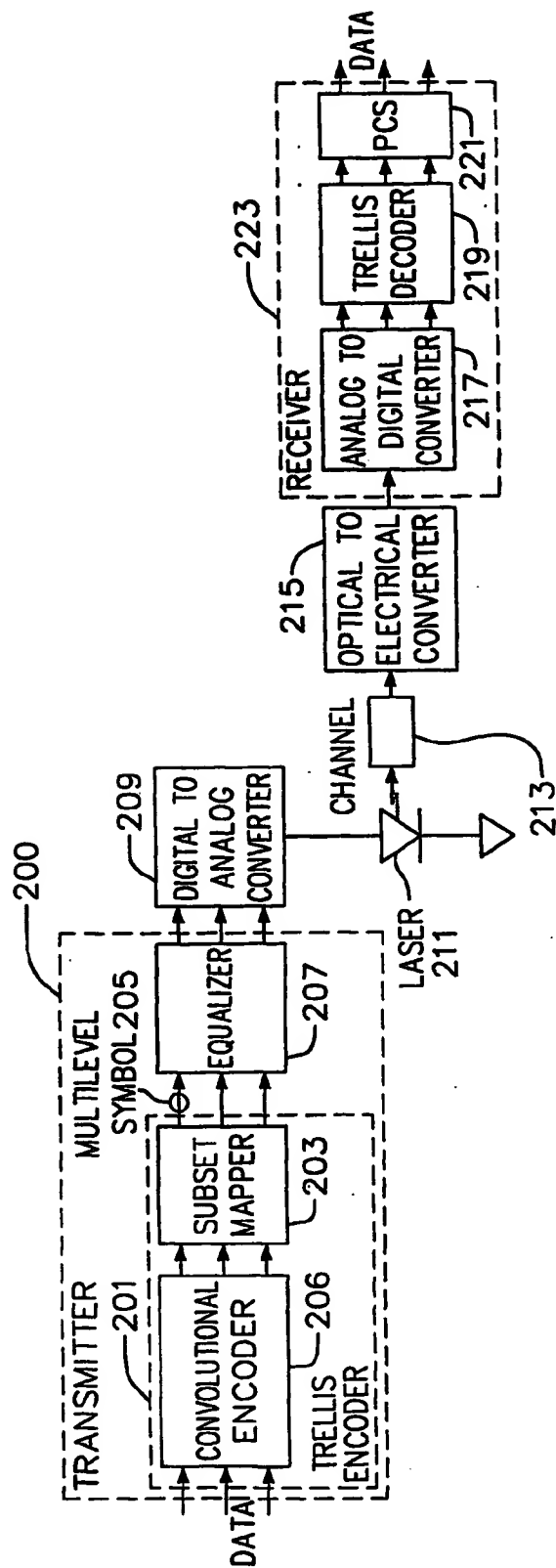


FIG. 3

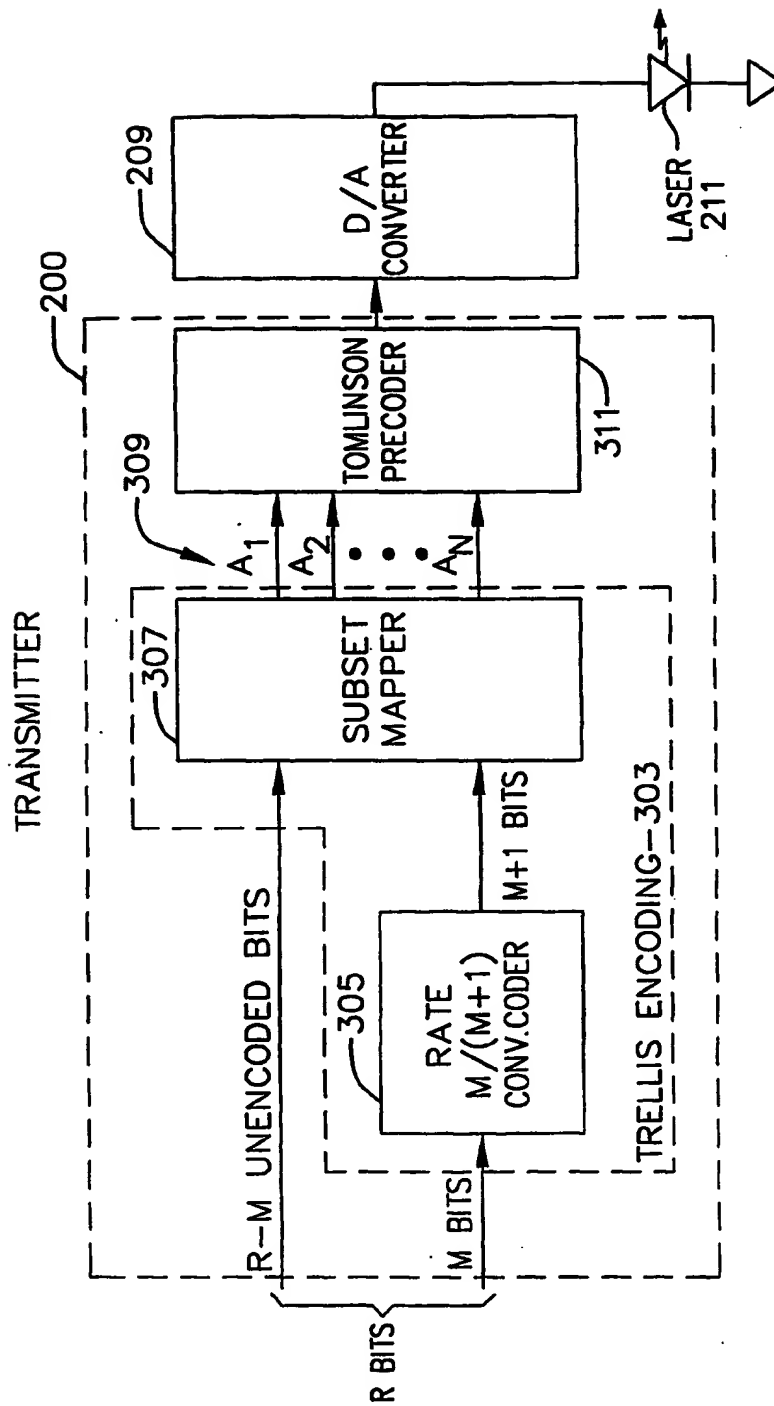


FIG. 4

TOMLINSON-HARASHIMA PRECODING (THP)

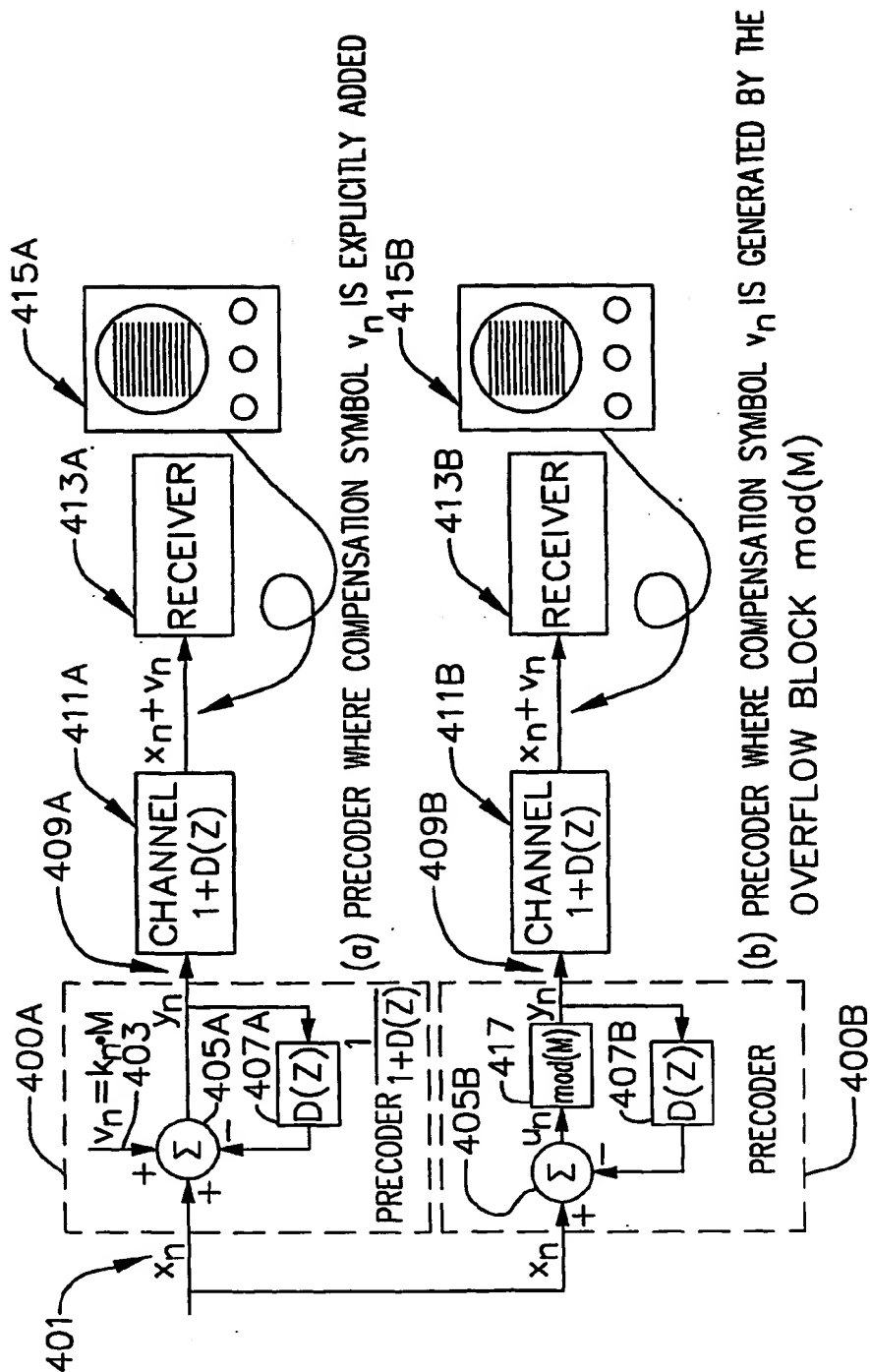
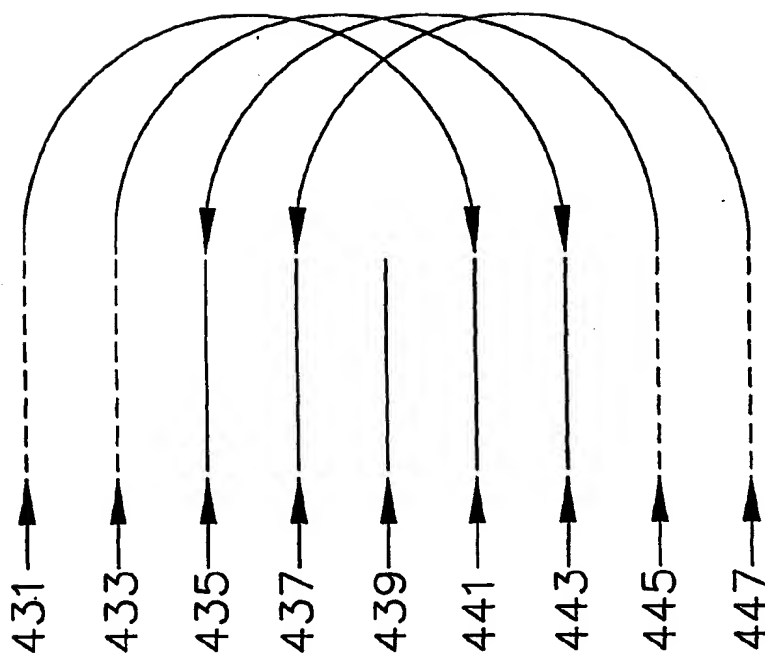
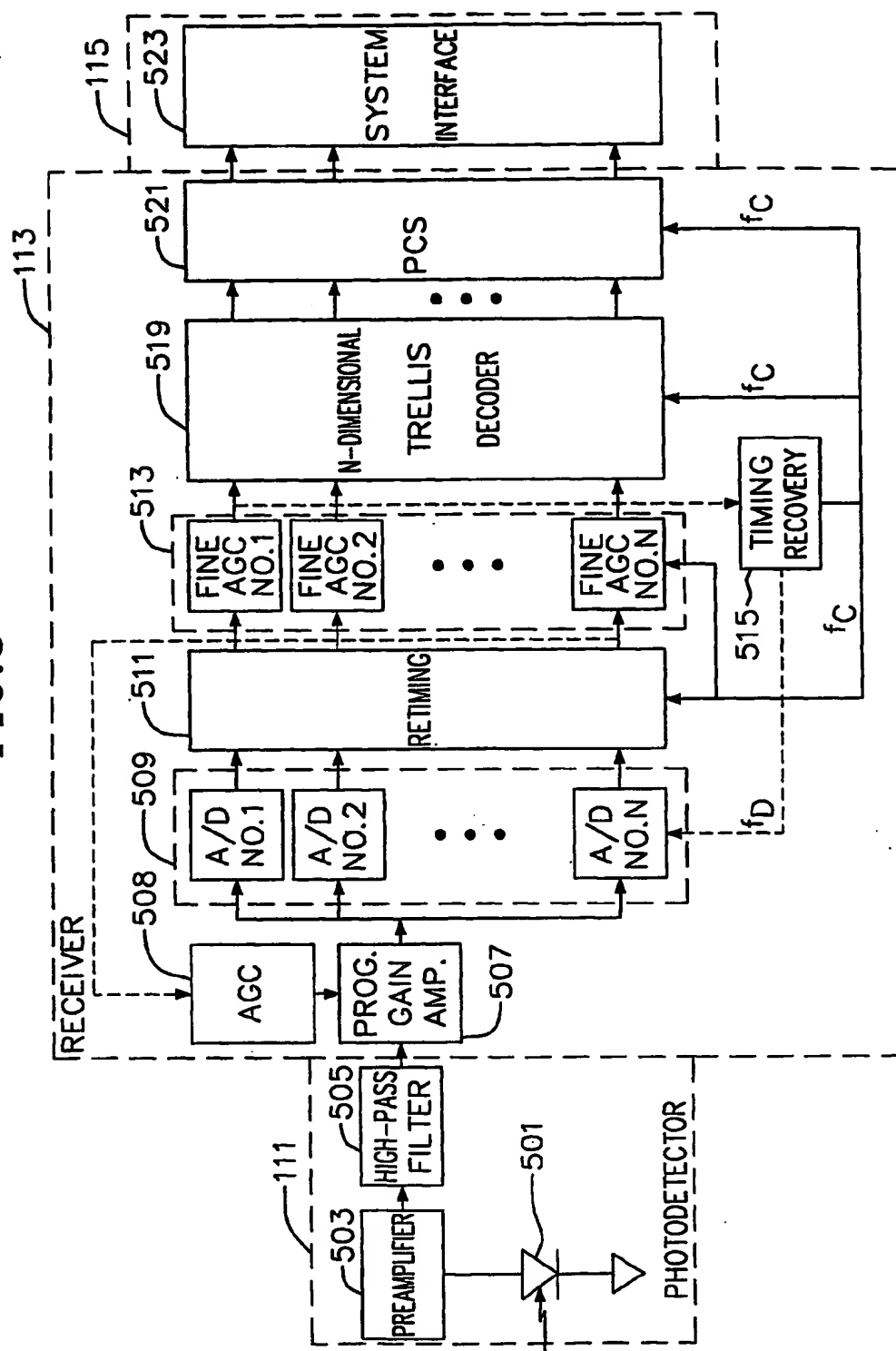


FIG. 4a



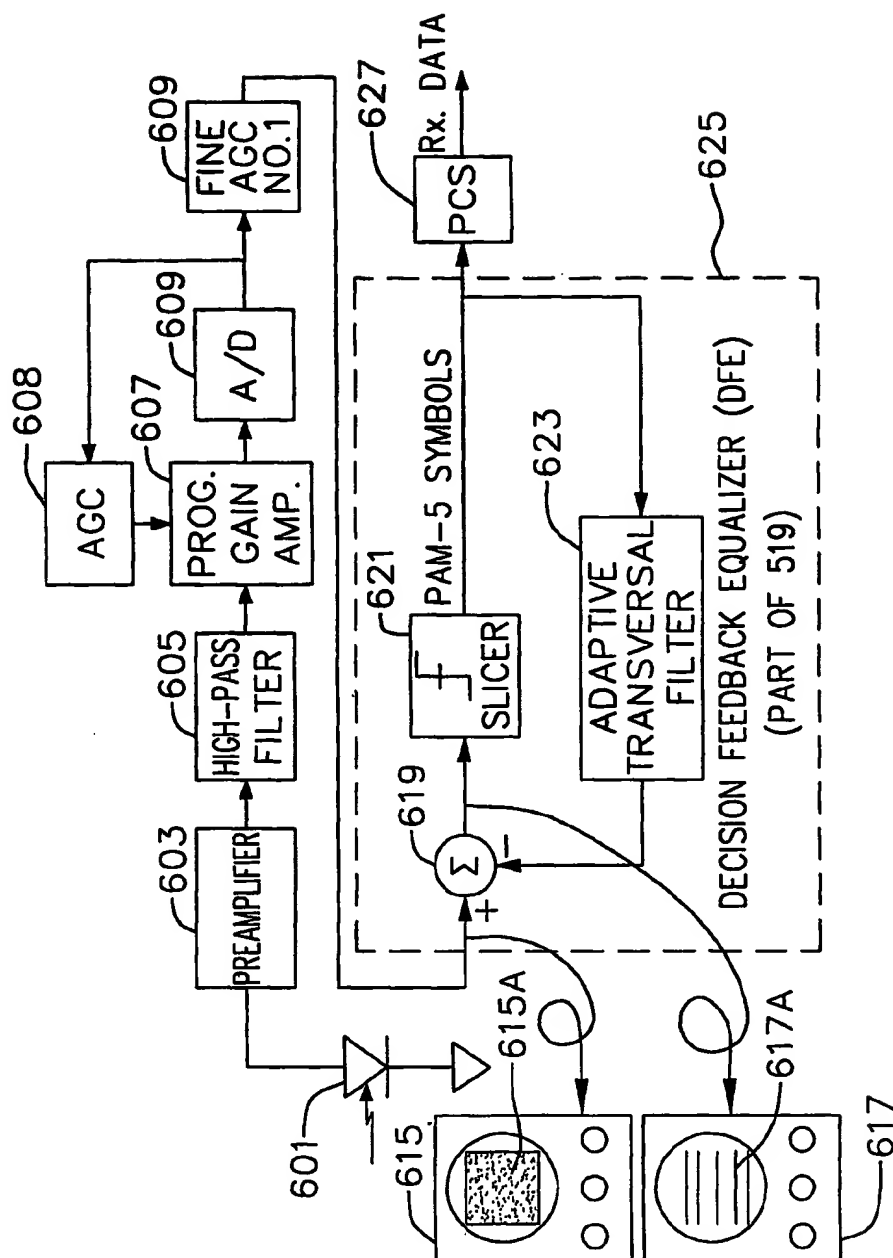
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FIG. 5



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FIG. 6



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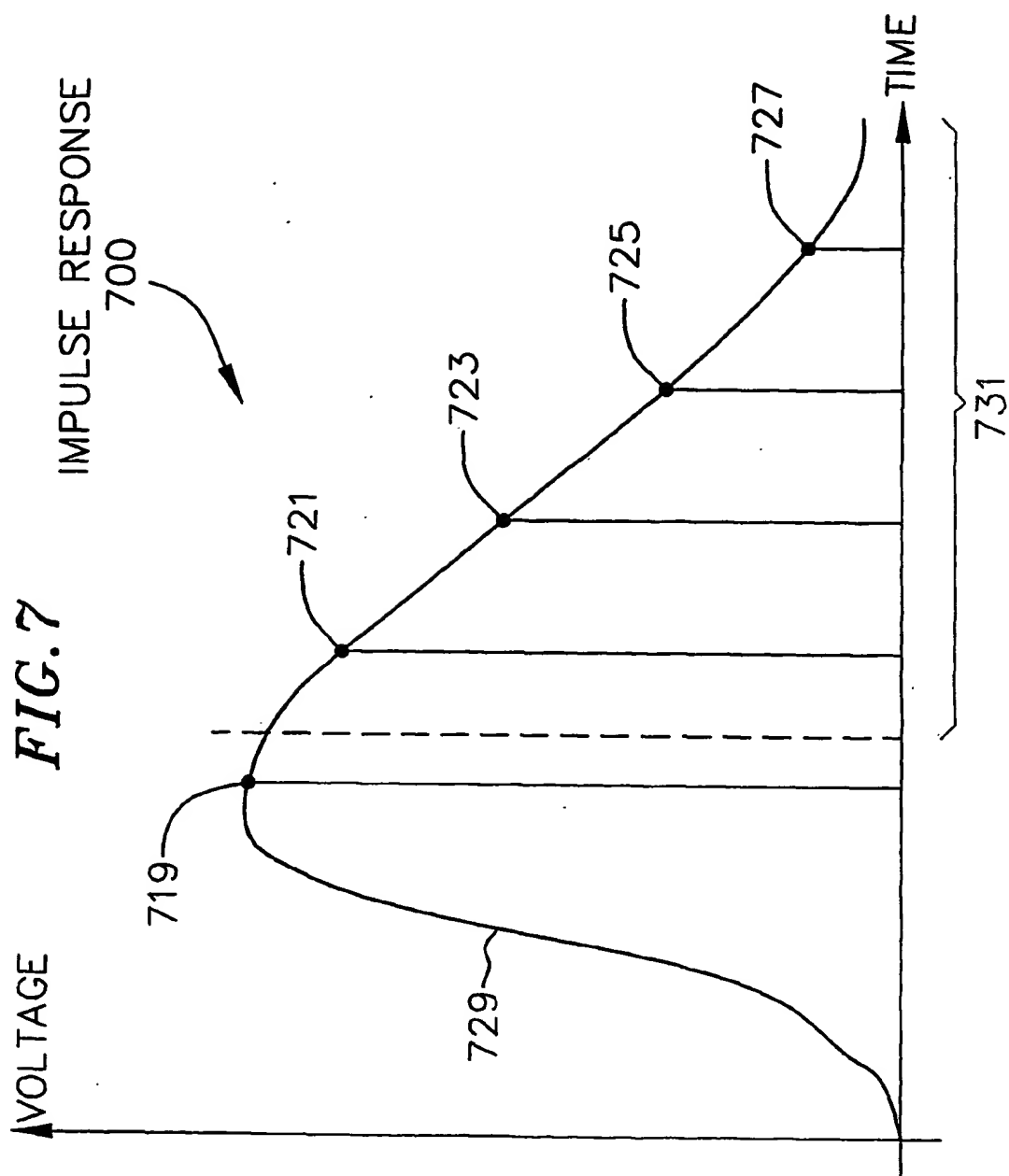
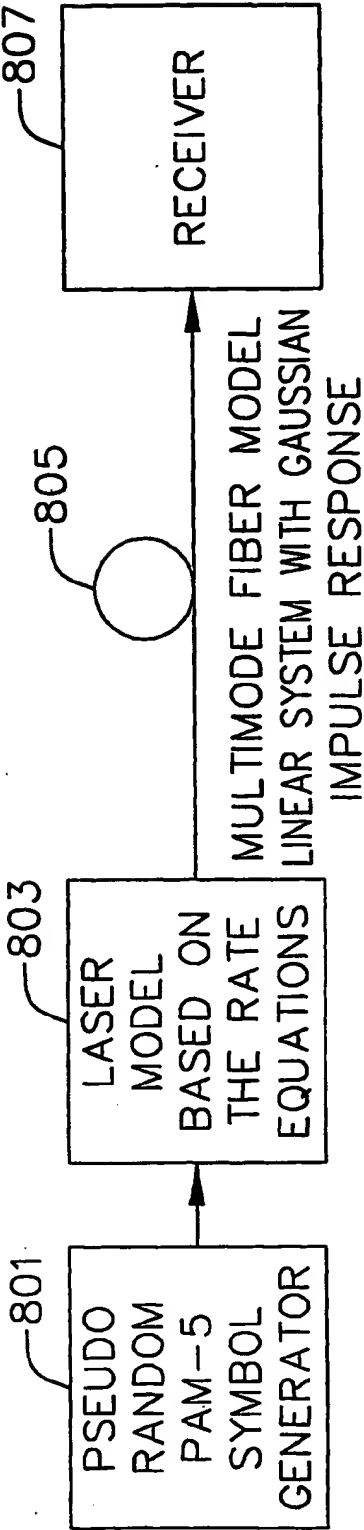


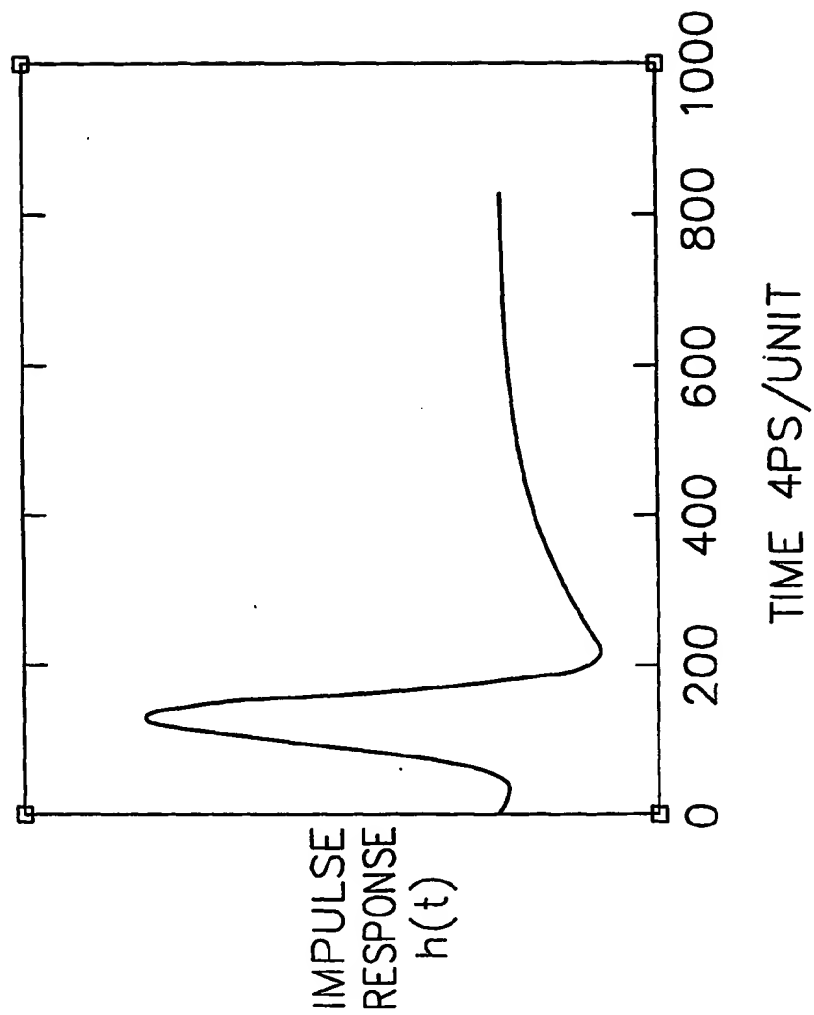
FIG. 8

CHANNEL MODEL

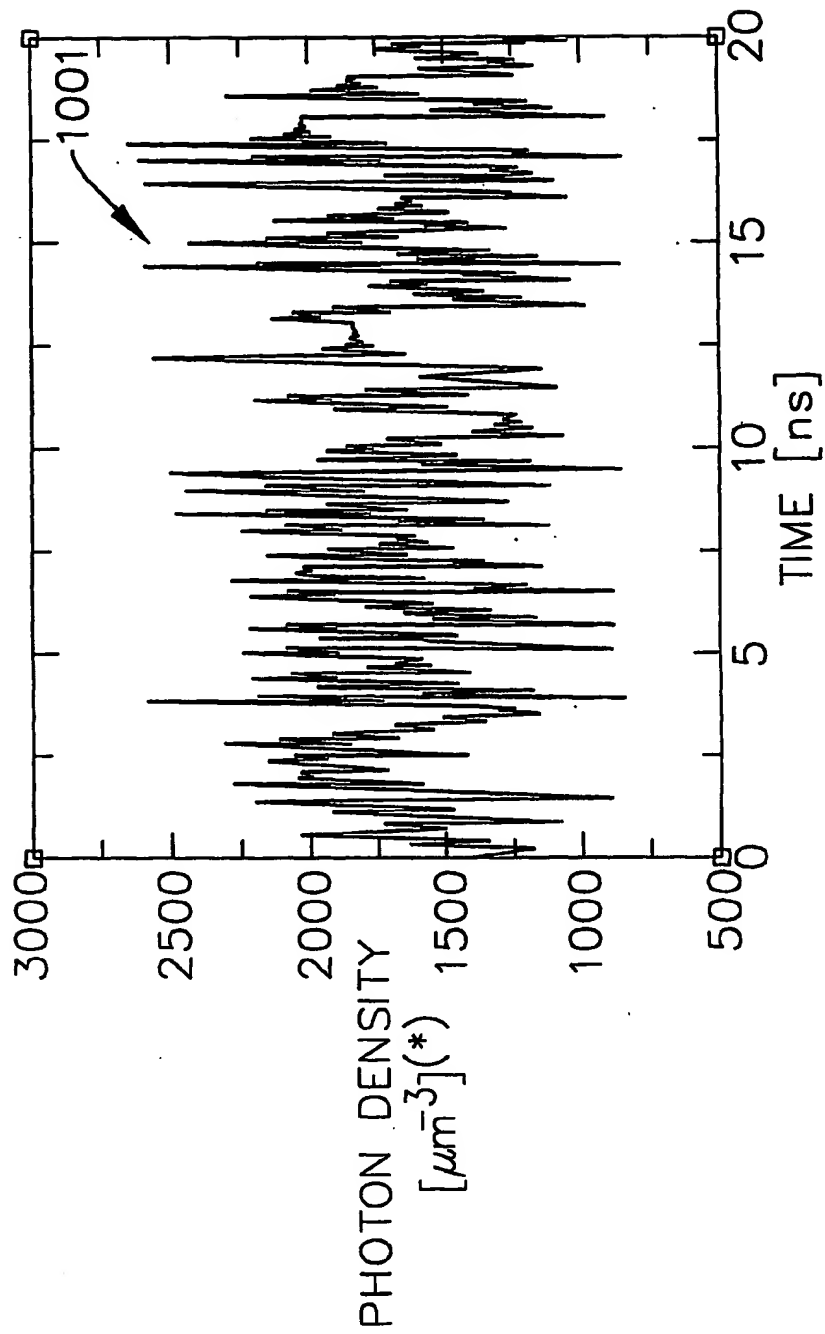


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FIG. 9



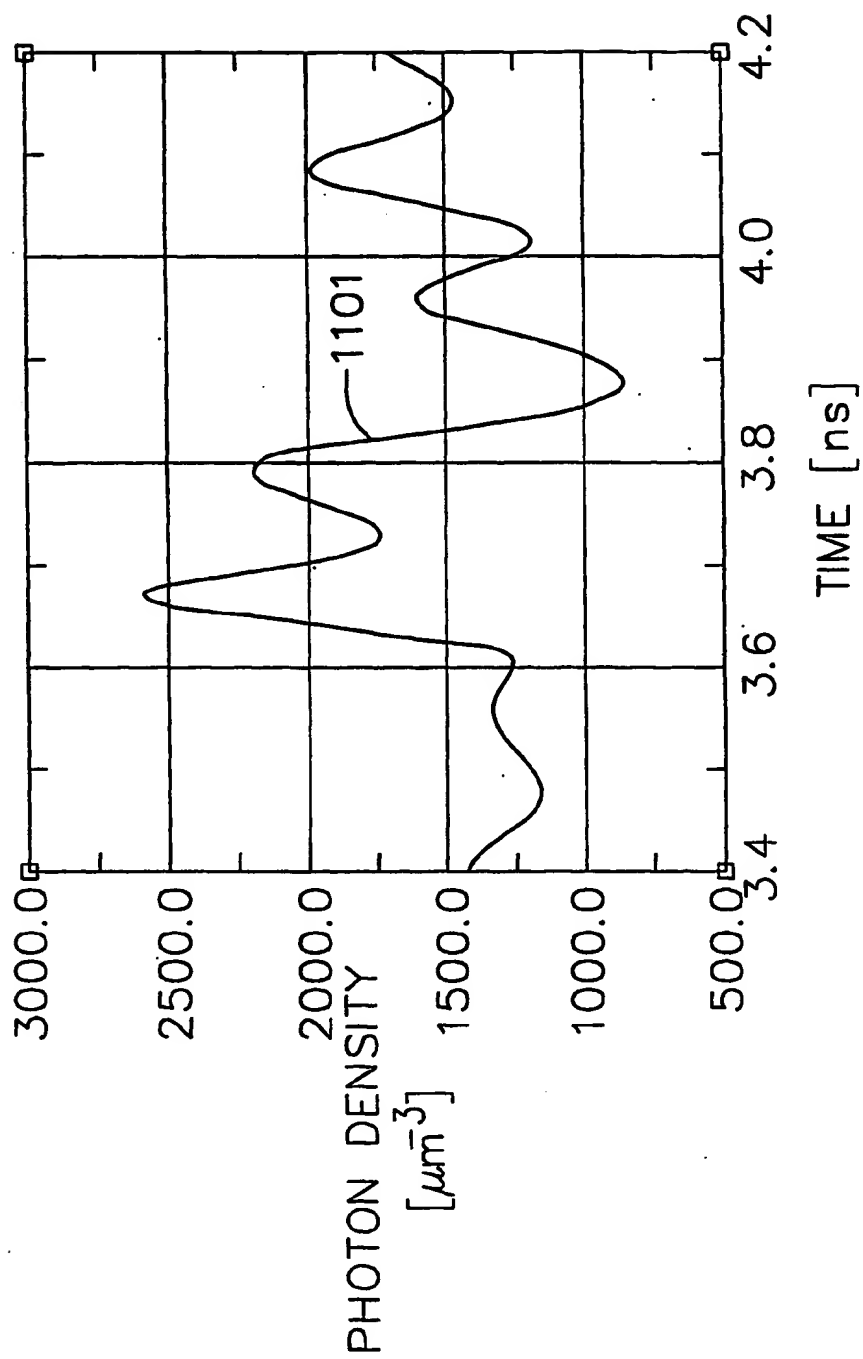
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FIG. 10

(*) CONSISTENT WITH A BIAS CURRENT OF 60mA

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FIG. 11



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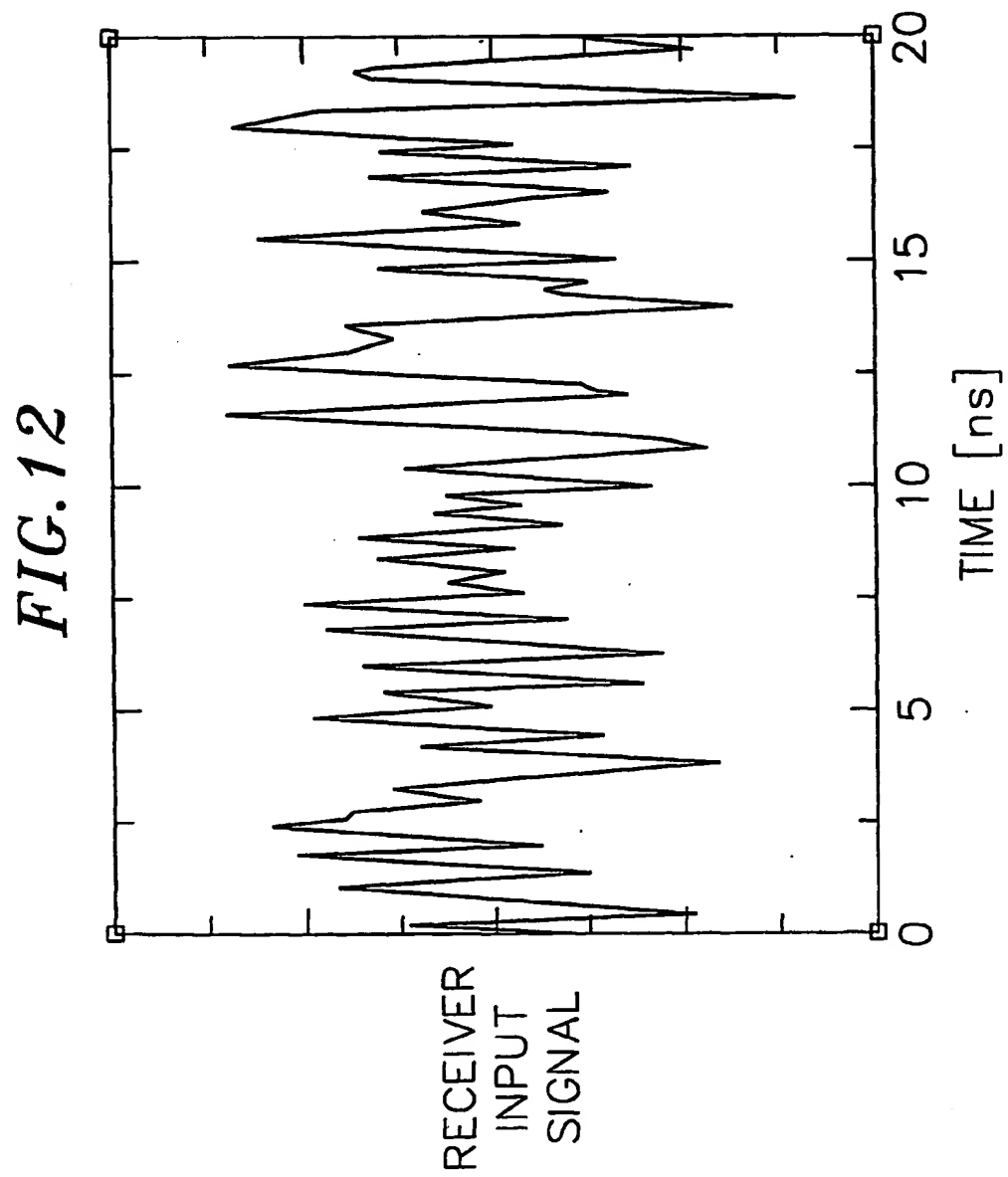
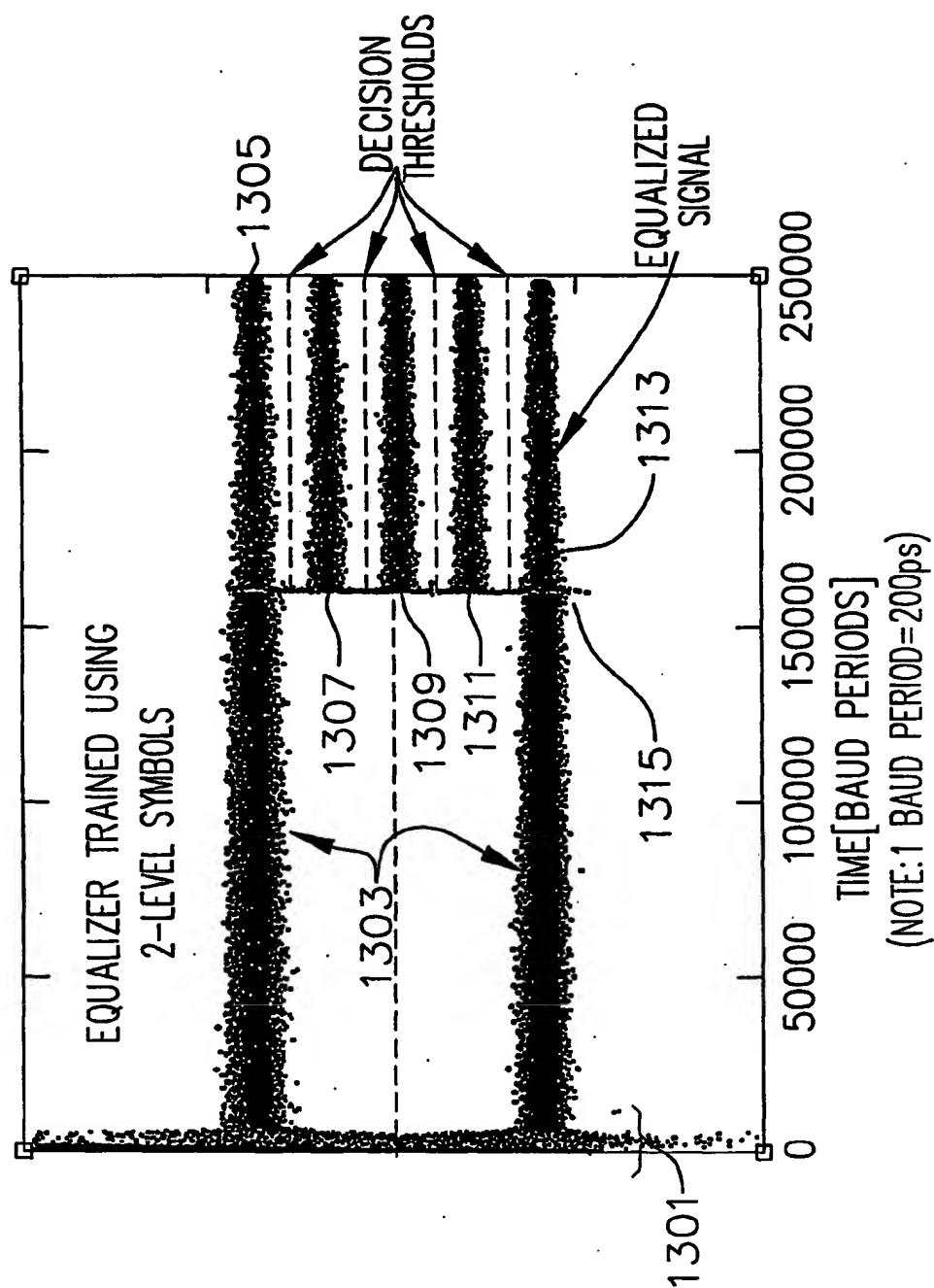


FIG. 13



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